Comparison of Speed-Acceleration Profiles from Field Data with NETSIM Output for Modal Air Quality Analysis of Signalized Intersections

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New vehicle modal emissions rate models will assess emissions as a function of specific operating mode or engine load surrogates. These new models require that vehicle activity be input by fraction of time spent in different operating modes. However, the ability to realistically model on-road modal vehicle activity currently limits the implementation of these models. Few data on how vehicles operate in a real-world setting exist. Simulation models offer attractive advantages for modal modeling. They are readily available and generally can be used with both simple and detailed data input. Simulation models were developed to model the impacts of signal timing, incidents, or design features on traffic flow and perform well for these applications. However, simulation models, such as CORSIM, use theoretical profiles of vehicle acceleration and speed relationships that have not been validated in the field. To determine the feasibility of using simulation models to predict on-road speed-acceleration profiles and to identify potential problems in their use as such, a study intersection was modeled in NETSIM, and the simulation output was compared with data collected from field studies of signalized intersections. Analyses of the simulation output and field data indicate that NETSIM does not adequately simulate instantaneous modal vehicle activity. NETSIM intersection activity shows higher fractions of hard accelerations [≥ 9.7+ km/h/s (6 mph/s)] than are demonstrated by field data for the study intersection. For midblock, the results indicate that field data demonstrate a much greater distribution of speeds and accelerations than the distribution modeled by NETSIM.

An abundance of research demonstrates that under most on-road operating conditions, actual vehicle emissions differ dramatically from those predicted by traditional mobile source emissions models (*1–3*). Deviations from average driving behavior can produce dramatic increases in emissions. In some cases the bulk of emissions from a vehicle trip may be attributed to a small fraction of the vehicle's operation. In particular, events of high engine loading (enrichment) contribute disproportionate emissions compared to those from normal stoichiometric operation (*4*). Increases in emissions of several magnitudes have been reported with hard accelerations and other loading events (*2,5–8*). Specifically, engine load is a variable that produces significant emissions rate differences. Emissions associated with engine load are a function of vehicle type, engine type, vehicle velocity and acceleration (inertial load and wind resistance load), roadway grade, and accessory use, such as air conditioning.

Current emissions rate modeling is based on the MOBILE family of models, which use an aggregate representation of on-road vehicle activity and assumptions of average driving behavior to estimate emissions. Corresponding emissions factors were developed from aggregate representations of vehicles based on the assumption that vehicles pollute similarly under an average range of speeds and vehicle miles traveled (*9*). This traditional approach neglects variations in driving behavior, especially extremes such as hard accelerations or stop-and-go driving under traffic signalization and congested conditions.

New emissions rate models, known as modal models, assess emissions throughout the entire driving cycle. These modal models estimate emissions as a function of specific operating mode or engine load surrogates. Initial indicators of engine load are vehicle speed and acceleration. To implement modal models, statistical distributions of vehicle activity corresponding to the amount of time vehicles spend in different speed and corresponding acceleration ranges are necessary. Other load variables such as grade and air-conditioner operation are also being included in advanced models. Once vehicle activity is disaggregated into speed and acceleration distributions, activity-specific load-based emissions rates are applied to estimate emissions. This approach is widely accepted as a more theoretically accurate approach for the provision of realistic estimates of mobile source emissions (*3–5,7,10*).

VEHICLE ACTIVITY MODELS

Although a modal approach to emissions modeling offers promising benefits, actual implementation is limited by the ability to realistically model on-road modal vehicle activity. Currently, few data describe how vehicles operate in a real-world setting. A report from the NCHRP (*11*) is one of the few sources that offers information on actual vehicle operation in terms of acceleration-speed activity. The report presents passenger car data, based on test studies with a single vehicle, a 1970 Chevrolet Impala sedan, driven over a test course. Test results indicate a linear relationship between speed and acceleration for passenger cars on zero grade, given by

$$A = a_o[1 - (V/V_m)] \tag{1}$$

where

a = acceleration capability at speed V,
a_o = maximum acceleration for speeds ≈ 0,
V = vehicle speed, and
V_m = a pseudo-maximum speed indicated by the linear relation between acceleration and speed when data are fitted in the normal operating range.

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According to Equation 1 and data presented in the report, maximum acceleration is achieved at zero speed and linearly decreases as speed increases. Maximum acceleration is a linear function of the inverse of the weight/horsepower ratio (*11*). Major drawbacks to the test study are that data were limited to one older-model-year vehicle on a fixed test route and the relationship describes the upper bound of the speed-acceleration curve rather than a distribution of the speeds and accelerations expected under normal vehicle operation.

To apply a modal model with load-specific emissions factors, more detailed vehicle activity data are necessary. More recent efforts undertaken by Grant (*12*) are aimed at statistically relating observed speed-acceleration characteristics on freeways as a function of vehicle class, traffic flow, and geometric highway parameters. This new approach uses aggregate measures of flow and roadway geometry to predict the important load-related measures of flow. Although Grant's methods work for freeway segments in Atlanta, the general methods have yet to be applied to the more complex traffic flow conditions that occur on nonfreeway roads.

SIMULATION MODELING

The next logical step in modeling is use of simulation for generation of modal activity. Engineers already simulate various transportation applications, such as the effects of different signalization schemes on traffic operation, and several traffic simulation models are capable of modeling individual vehicles in a traffic network.

Simulation models offer attractive advantages for modal modeling. They are readily available and generally allow both simple and detailed data input. A major advantage to simulation modeling is the ability to make multiple runs and compare different scenarios, such as comparing the effect of different traffic timing plans on individual vehicle delay. The use of simulation models for signalized intersections and downstream links is especially promising because intersections are locations of significant modal activity. Along signalized links, vehicle activity is particularly affected by intersection characteristics such as cycle length, which can easily be modeled by simulation.

However, simulation models usually use theoretical profiles of vehicle acceleration and speed relationships. The algorithms were intended to model gross measures of traffic activity, such as changes in cycle length or the effect of an incident. The models have been validated under these conditions and perform well for the applications for which they were developed. Internal algorithms, however, remain unvalidated for prediction of the activity of an individual vehicle. Additionally, most models are incapable of integrating temporal and spatial characteristics of traffic and roadways.

The purpose of this paper is to explore whether simulation models can be used to output realistic estimates of individual-vehicle activity and to identify drawbacks in their use. To accomplish this, a single study intersection was modeled by using simulation runs from NETSIM, the nonfreeway, urban traffic simulation module of the TRAF (CORSIM) traffic simulation model family. Instantaneous speed-acceleration outputs from NETSIM for the study intersection were compared with actual field data. As part of a cooperative grant from the Environmental Protection Agency and FHWA, research has been conducted at the Georgia Institute of Technology (Georgia Tech) to validate actual vehicle behavior at signalized intersections and along roadway links between signals. The viability of using NETSIM for modal modeling is explored, and field data and NETSIM output for the single intersection are compared.

Field research, to date, has involved the collection of vehicle activity profiles under a variety of operating conditions, such as with different geometric and operational parameters. With collection of actual speed-acceleration profiles, statistical distributions of modal vehicle activity as a function of operational and geometric differences are developed. The ultimate goal of the vehicle activity validation research is to develop statistical distributions of vehicle data that relate speed-acceleration profiles of vehicles to roadway characteristics such as grade, location along link, queue position, or volume of roadway to physical capacity. Statistical distributions can be output into fractions of time spent in different speed-acceleration ranges (*12*). Later, the activity can be linked with mode-specific emission rates to provide input to both regional and microscale air quality models.

The accuracy of speed-acceleration profiles used as inputs to transportation-related air quality models is important. However, collection of field data is difficult and expensive. Consequently, use of validated simulation models would be advantageous.

NETSIM

NETSIM is a microscopic, stochastic simulation program that models traffic movement on urban street networks (*13*). Simulation input parameters include link layout, volumes, turning movements, signalized control, grade, and link lengths. Major advantages of NETSIM are that vehicles are represented individually and operational performance is uniquely calculated second by second. Vehicle movement is controlled by car-following logic, as well as response to traffic control devices, pedestrian activity, transit operations, interactions with surrounding vehicles, and other factors that influence driver behavior on the basis of a fixed-time, discrete event simulation. An integral part of the NETSIM program is the use of random seeds to generate vehicle and driver characteristics, represent movements, free-flow speed, gap acceptance, queue-discharge headways, and so forth.

Rathi and Santiago (*13*) indicate that NETSIM is able to model most operational conditions that may be expected to occur in an urban street network. The model accounts for bus operation, short- and long-term events, and parking activity (*14*). NETSIM has been modified by Georgia Tech and other researchers to provide the capability of storing second-by-second vehicle trajectories by position for each vehicle in the simulation network. Given the detailed analysis capabilities of NETSIM, the model is a logical choice for use in the creation of speed-acceleration distributions in modal emissions modeling (signalized intersections and associated links).

Time, instantaneous speed, acceleration, and link position are calculated for each vehicle in the network. Each vehicle attempts to maintain a randomly generated "desired" speed on the basis of link free-flow speeds. The range of speeds that a vehicle undergoes along a link is influenced by traffic control and interference with surrounding vehicles. The acceleration rates corresponding to each instantaneously generated speed are constrained by car-following logic and an upper-bound maximum acceleration as a function of speed. The maximum acceleration rate is determined by a linear speed-acceleration relationship, with maximum acceleration occurring at zero velocity and with zero acceleration occurring at the maximum velocity. The relationship is similar to that reported by NCHRP (*11*). TRAF, version 5.0, was used in the analyses reported here and allows user-defined maximum acceleration at zero speed and maximum speed when acceleration is zero on dry, level roads for a specified vehicle type (*14*). A later version of the program allows user-defined maximum acceleration rates for specified speed ranges (*15*).

FIELD DATA COLLECTION METHODOLOGY AND ANALYSIS

Field data for vehicle activity profiles were collected with hand-held laser range-finder (LRF) devices at the signalized intersections being studied. These laser guns are capable of measuring the distance to an object at a high sampling frequency (238.4 distance measurements per second) with a manufacturer's accuracy specification of 15.24 cm (6 in.) root mean squared over 762 m (2,500 ft). The directionality of the laser beam allows the tracking of a single vehicle in a traffic stream, facilitating the capture of a vehicle trace over a range of modal activity. The data-collection procedure consisted of an operator "locking" the laser gun onto a selected vehicle and then following that vehicle until loss of lock occurred. Vehicles were randomly sampled by capturing the next available vehicle in each lane studied. Data for each vehicle observation were downloaded from the LRF and were stored as a unique file on a data card. Data collected by the LRFs are later processed by using a C program that calculates and outputs instantaneous speed, acceleration, time, and vehicle distance from the LRF. The program uses a smoothing algorithm to filter out readings when interference with the laser's lock on the vehicle being studied occurred (*16*).

To date, a total of 30 locations have been studied. Intersection selection criteria included locations where both a constant grade existed throughout the intersection and approaches and the geometric layout did not hinder accurate data collection. To adequately represent the range of activity along signalized roadways, sampling was conducted at the stop bar, behind the stop bar, and midblock.

Turning movement counts were recorded simultaneously so that vehicle activity profiles could later be related by operational characteristics such as volume to capacity. Attribute data for each vehicle (vehicle class, lane, queue position, etc.) were manually recorded during the data-collection process and were later matched with output from the LRFs. Individual vehicle traces were reported in 1-s intervals for the length of time that the vehicle was tracked. With this information, a speed and corresponding acceleration were identified for each second of activity. With attribute data attached, instantaneous speed and accelerations can be sorted by location, vehicle group, queue position, distance from the stopline, and so forth. Data are also sorted by location along a link so that critical locations for modal activity and possible enrichment can be identified.

TEST INTERSECTION

As stated previously, a single study intersection was used to compare NETSIM output with field data by using TRAF, version 5.0. Parameters for the sample intersection are as follows:

- Each approach has three lanes with an exclusive left turn lane;
- Lane widths are 3.66 m (12 ft);
- Approach volumes are as follows: eastbound, 1,317 vehicles per hour (vph); westbound, 900 vph; southbound, 1,289 vph; and northbound, 1,409 vph;
- Intersection operates at level of service (LOS) C as calculated from Highway Capacity Software (HCS) analysis (*17*);
- Average delay per vehicle, also from HCS analysis (*17*), is 22 s;
- Grade is zero; and
- Cycle length is 100 s, with green time equally split between the east-west and north-south approaches.

NETSIM allows certain parameters to be set by the user, including maximum achievable speed at zero acceleration, maximum acceleration at zero speed, and link free-flow speed. Default parameters were used, since they would be the only ones available in lieu of data collection and model calibration. The purpose of the study was to compare simulation output with field data to see how well the simulation model performs without additional calibration. As a result, default maximum acceleration was used. Even with calibration, however, the speed-acceleration relationship remains linear; only the outer bounds of the speed or acceleration range may be user defined.

TRAF's code was modified slightly to force output of individual vehicle data. Second-by-second output by individual vehicle yielded

- Simulation time,
- Vehicle identification number,
- Link identification number,
- Vehicle distance from the upstream node,
- A 0 or 1 code if the vehicle is caught in the queue,
- A 0 or 1 code if the vehicle is turning,
- Speed in miles per hour (feet per second), and
- Acceleration in feet per second per second.

A secondary program was used to sort the data by link, determine each vehicle's queue position, calculate the number of vehicles by link in each queue position, and create a speed-acceleration matrix. Delay is calculated per vehicle in the model. However, a factor of 22 s per vehicle, obtained from an intersection evaluation with HCS, was used to compute total intersection delay. This allowed consistent delay factors between the two models. Five simulation runs with different random seeds were made, and the results were averaged by approach.

For the field activity model, data that were representative of the study intersection were selected from among the 30 studied intersections. Representative factors included

- Similar distances between traffic signals,
- Similar intersection volumes,
- LOS C, and
- Similar grade.

For each approach of the study intersection, data were selected from all field data-collection locations that had characteristics similar to those of the approach. For example, to represent the northbound approach, data from data-collection locations that were operating at LOS C for an intersection with 1 percent grade or less, 1,220 to 1,610 m (4,000 to 5,280 ft) to the downstream intersection, and so forth, were used. For each approach of the study intersection, data from at least four data-collection locations were used.

Downstream conditions were uncongested with no queueing or spillback in both NETSIM and the field data. Although businesses were located along the data-collection areas, minimal driveway interactions were noted. NETSIM is not able to model driveway interactions per se. However, for significant driveway activity, additional nodes could be coded into the system. The average midblock speed for NETSIM was 64 km/h (40 mph), and the average midblock speed for the study intersections was 72 km/h (45 mph).

TABLE 1 Sample NETSIM and Laser Gun Output

NETSIM OUTPUT

Time (sec)	Link	ID	Distance (meters)	Lane	Speed (m/s)	Accel (m/s^2)	Turn	Queue
76	14	242	775	1	0.0	0.0	1	6
77	14	242	776	1	2.1	2.1	1	6
78	14	242	778	1	1.2	-0.9	1	6
79	14	242	780	1	1.2	0	1	6
80	14	242	812	1	1.8	0.9	1	6

LASER OUTPUT

Laser Offset: 3.0 meters Collection Date: 11-10-97 Start Time: 8:30

Time (sec)	Distance (meters)	Speed (kph)	Acceleration (kph/sec)
2.5	87	12.3	-0.2
3.5	104	12.1	-0.2
4.5	121	11.2	-0.8
5.5	137	10.3	-1.0

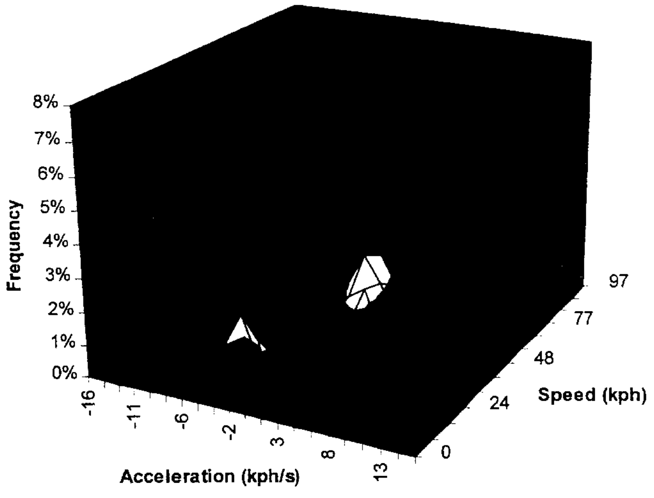

FIGURE 2 Three-dimensional speed-acceleration plots for field data [–76 to 76 m (–250 to 250 ft)] from the stop bar.

To ensure that actual vehicle profiles (not factors such as unequal volumes) would be compared, NETSIM output was used to determine the number of vehicles in queue for the study hour by approach. Field data were normalized so that an equal number of vehicles by queue position and data for the length of the study section were represented. A delay factor of 22 s per vehicle was used as described earlier so that idle times were comparable. Data for heavy vehicles were collected in the field and can be modeled by NETSIM but were not included in this phase of the research. Sample NETSIM and laser gun output for field data are shown in Table 1.

RESULTS

Comparisons of NETSIM and field data for the same sample intersection demonstrate significant differences. Figures 1 and 2 are three-dimensional frequency plots of speed and acceleration at the intersection location. Data are reported for a distance 76 m (250 ft) before and 76 m (250 ft) after the intersection stop bar. In estimating the percentage of vehicle activity by bin, stop delay was minimized to 1 s per vehicle so that high delay values did not overwhelm all other vehicle activity fractions. Figure 3 shows the percentage of time spent in different acceleration categories. Table 2 shows the fractions of vehicle activity spent in various acceleration ranges. As shown, NETSIM reports four times more seconds of hard accelerations than were recorded in the field data [≥9.7 + km/hs (6 mph/s)]. Figure 4 shows the percentage of time spent in each speed range for each model. Note that NETSIM underpredicts higher speed ranges [80 to 105 km/h (50 to 60 mph)] for the study intersection.

The subset of midblock activity data was also analyzed. Figures 5 and 6 show a frequency plot by speed and acceleration for vehicle activity midblock, 610 m (2,000 ft) downstream from the study intersection. Figures 5 and 6 also give the frequency of time spent in each acceleration or speed range. Table 2 condenses the vehicle data by the total percentage of time spent in each acceleration bin. Unlike intersection activity, NETSIM predicts few midblock acceleration events, once a vehicle achieves its desired speed, and the modeled acceleration activity remains fairly static. NETSIM also has a narrow range of midblock speeds [40 to 89 km/h (25 to 55 mph)]. Field data

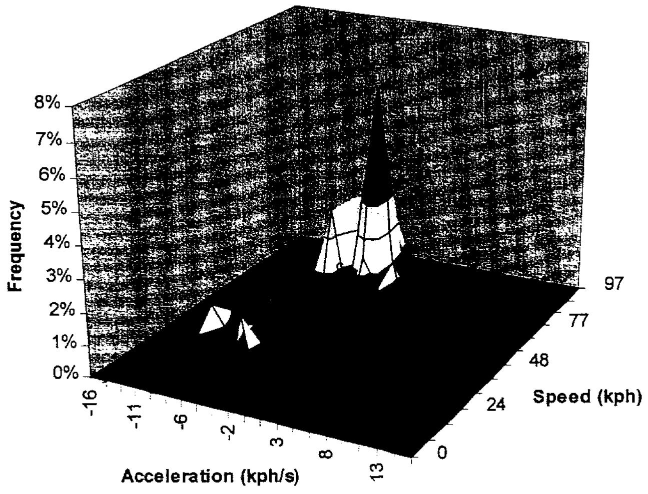

FIGURE 1 Three-dimensional speed-acceleration plots for NETSIM data [–76 to 76 m (–250 to 250 ft)] from the stop bar.

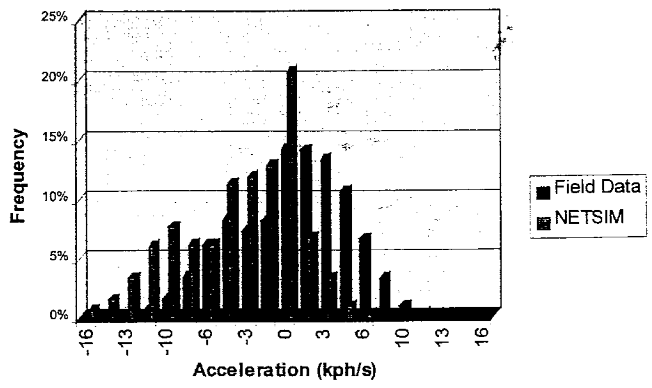

FIGURE 3 Comparison of percent time spent in each acceleration range for field data and NETSIM [–76 to 76 m (–250 to 250 ft)] from the stop bar.

TABLE 2 Vehicle Activity

Acceleration Mode	Percent Activity			
	Field Data at Intersection	NETSIM at Intersection	Field Data Midblock	NETSIM Midblock
9.7+kph/s (6+ mph/s)	1	4	1	0
4.8 kph/s (3+ mph/s)	22	20	4	0
-4.8 kph/s (-3 mph/s)	21	20	11	0
9.7 kph/s (-6 mph/s)	3	1	0	0

show much greater acceleration variations and wider speed ranges. Figure 7 shows a comparison of the percentage of time by speed range at midblock for both NETSIM and the field data. As shown, NETSIM has much narrower speed ranges than those demonstrated by the field data. As described above, no downstream queuing or significant driveway interaction that would influence variations in speed and acceleration in the field data was noted. As shown in Table 2, 1 percent of field data experienced high accelerations [≥9.7 km/h/s (6 mph/s]), whereas 4 percent of field data had observations with accelerations of greater than 4.8 km/h/s (3 mph/s). Field data speeds ranged from 0 to 105 km/h (65 mph).

A comparison is also provided for the first vehicle in the queue. Intuitively, the first vehicle has the greatest potential for maximum acceleration since it usually enjoys unconstrained downstream flow. Prior research indicates that the first vehicle in the queue is more likely to experience "hard" accelerations at the stop line than at other queue positions (*18*). Data were extracted from NETSIM for 212 "first-in-the-queue" vehicles, and field data were provided for 37 "first-in-the queue" vehicles. Even with data for roughly three times as many vehicles, the NETSIM simulation data show much less variation than the field data. Additionally, acceleration peaks are noted in the speed range of 11 to 35 km/h (7 to 22 mph) for the field data and from 0 to 16 km/h (0 to 10 mph) for the simulation data. A plot of speed versus acceleration for data 0 to 76 m (0 to 250 feet) from the stop bar for the first vehicle are shown in Figure 8.

A second step in comparing NETSIM output with field data was to apply emissions factors to estimate emissions. Speed-corrected factors from MOBILE5a were used for the analysis. Emissions factors from the Georgia Tech MEASURE geographic information system-based air quality model were also applied to the data to determine differences in emissions estimates that would result from the use of field data versus the use of simulation results. MEASURE uses regression tree analysis on vehicle emissions data to estimate mode-specific emission factors (*19*). Speed-acceleration matrices for the two data sets were prepared. The data sets represented vehicle activity for 402 m (1,320 ft) above to a location 402 m (1,320 ft) below the intersection of interest. The results are presented in Table 3.

Use of the NETSIM speed-acceleration profiles with MEASURE or MOBILE5a emission rates resulted in emissions significantly different from those predicted by using the field-collected speed-acceleration profiles. With either emission rate model, the emissions predicted from the NETSIM data were significantly higher. However, the emissions difference was even more pronounced when the estimates were made by using the MEASURE modal emission rate model. This illustrates the possible ramifications in using inaccurate or theoretical (of unknown accuracy) vehicle activity profiles with modal emissions models. The actual impact will vary by location, fleet composition, time spent idling at the intersection, and so forth. Ultimately, impacts will depend on the sensitivities of emerging emission factor models to mode-specific variables.

CONCLUSIONS

Results of a comparison between NETSIM simulation output data and representative field data for a test intersection indicate that standard NETSIM outputs may not adequately represent actual vehicle activity for use in modal emissions modeling. In this study of intersection activity, NETSIM predicted higher fractions of hard accelerations than the fractions demonstrated by field data for locations

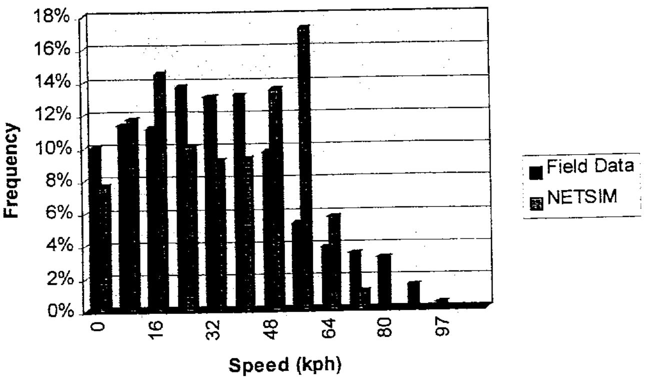

FIGURE 4 Comparison of percent time spent in each speed range for field data and NETSIM [−76 to 76 m (−250 to 250 ft)] from the stop bar.

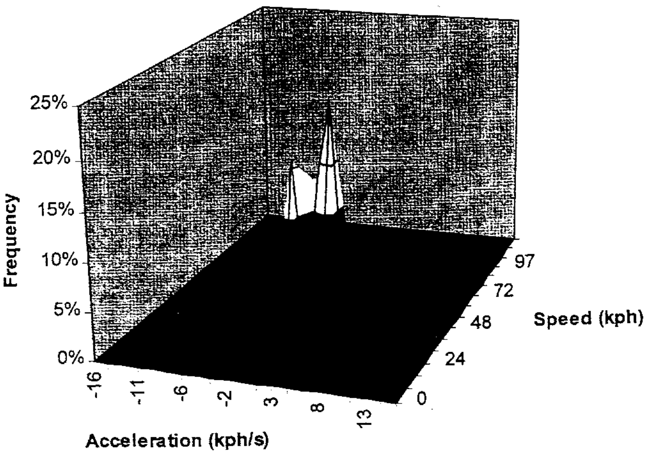

FIGURE 5 Three-dimensional plots for midblock NETSIM data.

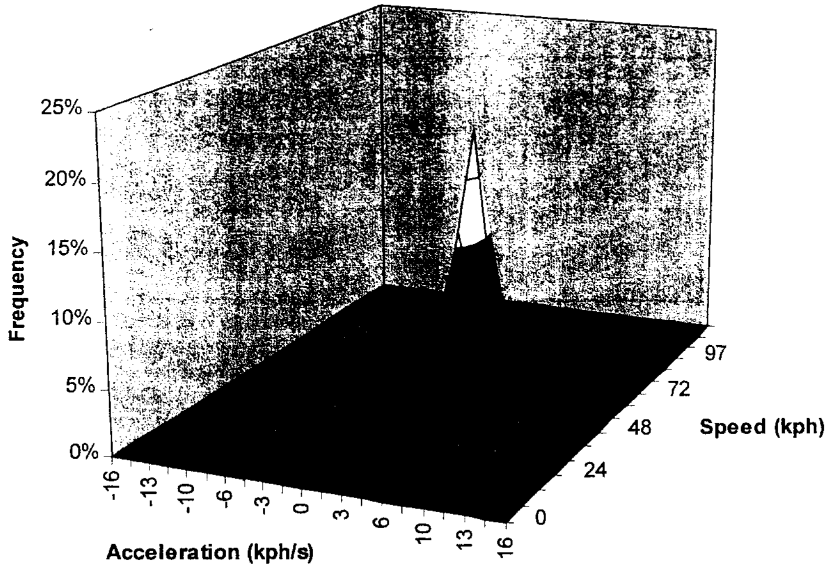

FIGURE 6 Three-dimensional plots for midblock field data.

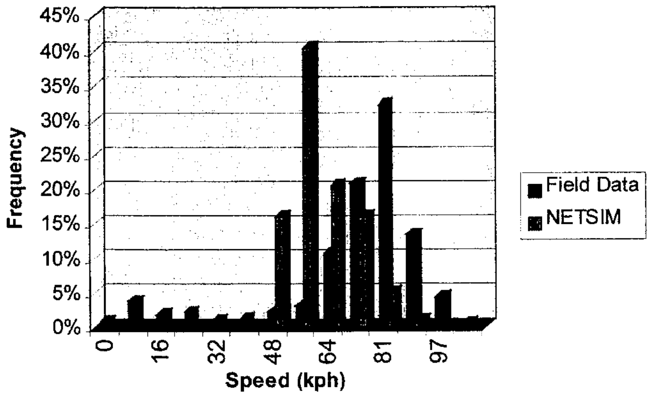

FIGURE 7 Comparison of percent time spent in speed ranges for midblock data.

around the actual intersection. Additionally, field data indicate that at midblock, vehicles undergo a much greater distribution of speeds and accelerations than the distributions modeled by NETSIM. The purpose of the study was to investigate whether or not NETSIM, as is, is capable of producing accurate estimates of microscopic vehicle activity for use in air quality modeling. Although in this study NETSIM was shown to overestimate emissions, the study was not intended to provide conclusive evidence that NETSIM underpredicts or overpredicts emissions. The results would vary for any number of factors such as different volumes, timing plans, or length between signalized intersections.

Even though the NETSIM model may be calibrated correctly to predict aggregate flows or speeds, it is not necessarily calibrated to provide accurate speed-acceleration profiles. Current research at Georgia Tech is now focused on calibration and program code changes that can be integrated in NETSIM such that modal activity

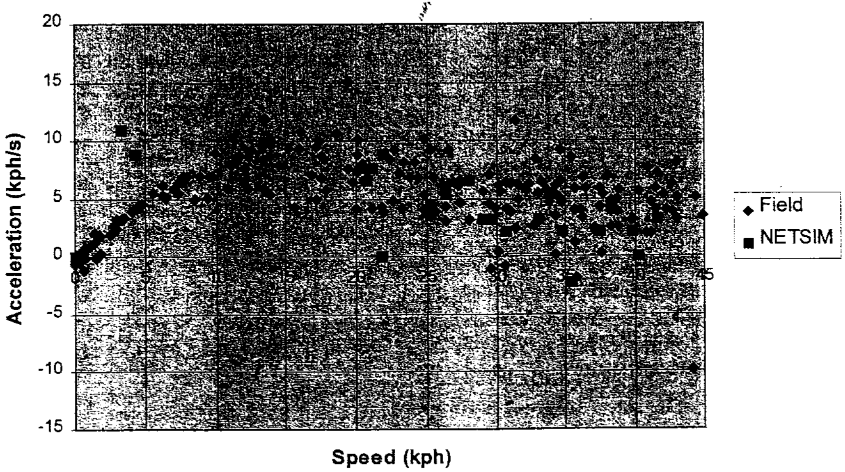

FIGURE 8 Comparison of field and NETSIM data for first vehicle in queue [stop bar to 76 m (250 ft)].

TABLE 3 Comparison of Emissions by Model Using MEASURE and MOBILE Outputs

Pollutant of Interest (grams/km)	Field Data Results with MEASURE	NETSIM Results with MEASURE	Field Data Results with MOBILE	NETSIM Results with MOBILE
CO	8.6	11.3	4.0	5.0
HC	0.4	0.5	0.4	0.5
NO	0.2	0.3	0.7	0.7

can be more accurately predicted (without sacrificing the accuracy of aggregate flow and other predictions used in signal timing and other modeling efforts).

If NETSIM or similar simulation models do not predict speed-acceleration profiles correctly, the ultimate impact is largely dependent on the emissions factors that will be applied to the data. Emissions predicted from modal emissions rate models, which predict significantly higher emissions at higher engine loads, will be adversely affected by errors in predicted speed-acceleration profiles, especially in the extreme speed-acceleration bins. When modal emission factors indicate that average speeds are a highly significant variable (as they are for oxides of nitrogen), NETSIM outputs are likely to underestimate modal emissions. When high accelerations at low to medium speed ranges are more significant, NETSIM has the potential to overrepresent emissions. However, even with traditional MOBILE emission factors, NETSIM output for the study intersection overrepresented emissions by 20 to 30 percent.

Field validation efforts for speed-acceleration profiles are labor-intensive and technically difficult. It is challenging to collect both complete ranges of vehicle activity along a signalized link and ranges of vehicle activity under changing operational characteristics. Although NETSIM did not adequately reflect on-road vehicle activity in this case, it may still prove to be a valuable tool in air quality analysis. Other intersections under different operating conditions continue to be studied in Atlanta, Georgia, and supplemental speed-acceleration calibration approaches are being investigated. The use of NETSIM or some other type of simulation may also be attractive when used in tandem with local field data. The simulation models could output total seconds of vehicle activity for the entire length of the approach on the basis of the number of vehicles in each queue position. This could then be combined with speed-acceleration fractions specific to different locations along the link on the basis of field data for locations with similar operational and geometric characteristics.

REFERENCES

1. Kelly, N. A., and P. J. Groblicki. Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles. *Journal of the Air and Waste Management Association,* Vol. 43, Oct. 1993, pp. 1351–1357.
2. LeBlanc, D. C., M. D. Meyer, F. M. Saunders, and J. A. Mulholland. Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment. In *Transportation Research Record 1444,* TRB, National Research Council, Washington, D.C., 1994, pp. 126–134.
3. Barth, M., F. An, J. Norbeck, and M. Ross. Modal Emissions Modeling: A Physical Approach. In *Transportation Research Record 1520,* TRB, National Research Council, Washington, D.C., 1996, pp. 81–88.
4. Guensler, R. Data Needs for Evolving Motor Vehicle Emission Modeling Approaches. In *Transportation Planning and Air Quality II* (P. Benson, ed.), ASCE, New York, 1993.
5. Barth, M., T. Younglove, T. Wenzel, G. Scora, F. An, M. Ross, and J. Norbeck. Analysis of Modal Emissions from a Diverse In-Use Vehicle Fleet. In *Transportation Research Record 1587,* TRB, National Research Council, Washington, D.C., 1997, pp. 73–84.
6. An, F., M. Barth, J. Norbeck, and M. Ross. Development of Comprehensive Modal Emissions Model: Operating Under Hot-Stabilized Conditions. In *Transportation Research Record 1587,* TRB, National Research Council, Washington, D.C., 1997, pp. 52–62.
7. Guensler, R., M. O. Rodgers, S. Washington, and W. Bachman. An Overview of the MEASURE GIS-Based Modal Emissions Model. In *Transportation Planning and Air Quality III* (T. Wholley, ed.), ASCE, New York, 1998.
8. Fomunung, I., S. Washington, and R. Guensler. Incorporating Modal Vehicle Activities in Estimating a NOx Emissions Model. *Transportation Research D,* in press.
9. Guensler, R., and D. Sperling. Congestion Pricing and Motor Vehicle Emissions: An Initial Review. In *Special Report 242: Curbing Gridlock: Peak Period Fees To Relieve Traffic Congestion,* Vol. 2. TRB, National Research Council, Washington, D.C., 1994, pp. 356–379.
10. Washington, S. Considerations for Developing New Mobile Source Emissions Models. Presented at 75th Annual Meeting of the Transportation Research Board, Jan. 1996, Washington, D.C.
11. St. John, A. D., and D. R. Kobett. *NHCRP Report 185: Grade Effects on Traffic Flow Stability and Capacity.* TRB, National Research Council, Washington, D.C., 1978.
12. Grant, C. *Representative Vehicle Operating Mode Frequencies: Measurement and Prediction of Vehicle Specific Freeway Modal Activity.* Dissertation. Georgia Institute of Technology, Atlanta, Aug. 1998.
13. Rathi, A. K., and A. J. Santiago. TRAF-NETSIM Program. *Journal of Transportation Engineering,* Vol. 115, Nov./Dec. 1990, pp. 734–743.
14. *TRAF User's Guide,* version 5.0. U.S. Department of Transportation and FHWA, March 1995.
15. FHWA. *Traffic Software Integrated System User's Guide,* version 4.2, March 1998.
16. Grant, C. *Laser Rangefinder (Laser Gun) Standard Operating Procedure (SOP).* Georgia Institute of Technology, Atlanta, May 1997.
17. *Special Report 209: Highway Capacity Manual,* 3rd ed. TRB, National Research Council, Washington, D.C., 1998.
18. Hallmark, S. L., R. Guensler, and J. D. Leonard II. Stopline Distributions of Speed and Acceleration for Signalized Intersections. Presented at 91st Annual Meeting of the Air and Waste Management Association, San Diego, Calif., 1998.
19. Washington, S., J. Wolf, and R. Guensler. Binary Recursive Partitioning Method for Modeling Hot-Stabilized Emissions from Motor Vehicles. In *Transportation Research Record 1587,* TRB, National Research Council, Washington, D.C., 1997, pp. 96–105.

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